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# Hybrid Additive and Microfabrication of an Advanced Micromirror Array


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## ABSTRACT

We have developed a hybrid conventional and additive manufacturing (AM) technique for the fabrication of a high fill-factor (99%) micro-mirror array design (10,000 1mm$^2$ mirrors). The micromirrors are driven with three degrees of freedom (DOFs)—tip, tilt, and piston—over large ranges (±10deg rotation and >±30µm translation) at high speeds (~40kHz small stepping rate), all with continuous closed-loop control. The capabilities of this new mirror array will extend the performance of a variety of high-impact technologies including: (i) optical switches, (ii) confocal microscopes, (iii) autostereoscopic display and image capture, (iv) microprojectors, (v) high speed focusable LIDAR or other imaging, (vi) micro-additive fabrication approaches that utilize principles of light steering (e.g., two photon polymerization or optical tweezers), and (vii) high-powered laser steering systems. The initial fabrication effort is focused on the generation of an independently controllable seven-mirror prototype. The fabrication process performance and limitations are described.


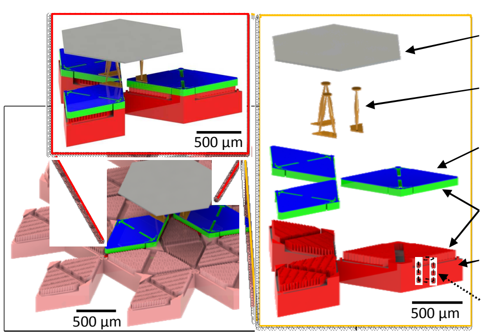


*FIGURE 1: Micromirror array design.*

## STRUCTURE

A seven mirror array is shown in Fig. 1 to illustrate the scale and components of the micromirror. Only the middle element is shown fully assembled. The micromirror array is composed of hexagonal unit cells, each of which contains three bipolar electrostatic comb drive actuator paddles, three decoupling flexure linkages and a hexagonal mirror. The actuators are the green/blue paddles which are anchored at two corners to the red actuation plate below and are free to rotate around a single axis.

## PROCESS OVERVIEW

The mirrors are assembled from i) a microfabricated actuation plate and ii) micro-stereolithographically generated hexapod flexures, which are printed onto the underside of iii) microfabricated silicon hexagonal mirrors. The finished structure is shown in Fig. 2. The process limitations were characterized for both the microfabrication and the AM side. An initial pick-and-place operation was used to generate a single assembled cell. An improved parallel assembly process is being developed for handling all 7 mirrors to generate the 7 element array.

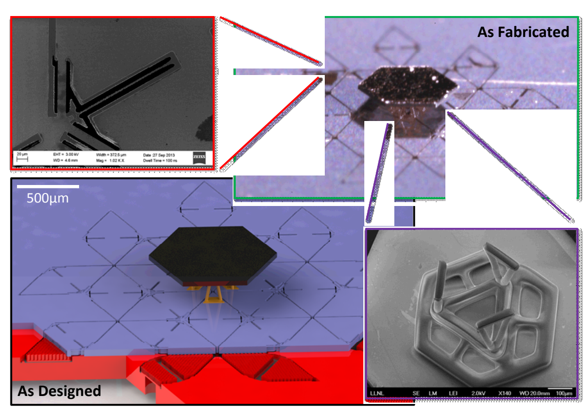


*FIGURE 2: Fabricated vs. designed structure.*

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[1]These are both first authors as their contributions to this paper are equal

## MICROFABRICATION

The actuation plate is made of two microfabricated single crystal silicon wafers, shown in Fig. 1 as the actuator paddle and the base plate. These two plates are aligned and fused together.

## MAIN PLATES

The ground paddles comprise the flexible moving rhomboid stage above each set of combs. These are all fabricated as part of a double-SOI single crystalline wafer. The top surface of the ground plate must be flat and smooth as it will form one side of the bond to the actuation plate. The combs on the ground plate are etched, producing the comb patterns within each paddle as shown in Fig. 3.

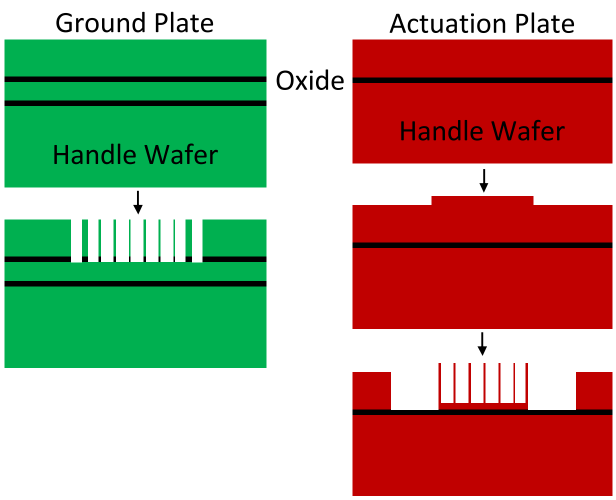


*FIGURE 3: Ground plate etching.*

The fabrication process next focuses on the actuation plate, which is the non-moving side with the isolated islands of combs. The actuation plate is started as an SOI wafer where the top layer is highly doped (conductive) Si, and the bottom layer is undoped (non-conductive) Si intended to act as the structural layer. Three conflicting requirements are found at the surface of this plate. 1) The top surface of the actuation plate must be flat and smooth as it will form one side of the bond to the ground plate. 2) The combs should slightly overlap one another to provide a smooth and uniform change in capacitance through the equilibrium position. 3) The combs should be made of single crystal Si to maximize their strength. The selected growth of a uniform layer of expitaxial silicon over the comb islands was found to meet all three of these requirements. The surface is patterned and the combs are etched to produce electrically isolated comb 'islands'.

## BONDING AND BACK ELECTRONICS

The two wafers are now flipped and a BCB bond was first used to attach the wafers. Later efforts have focused on wafer fusion bonding for the conductive contact and higher alignment accuracy. This step determines the comb alignment, and so must be done to high accuracy. The present target is <2μm.

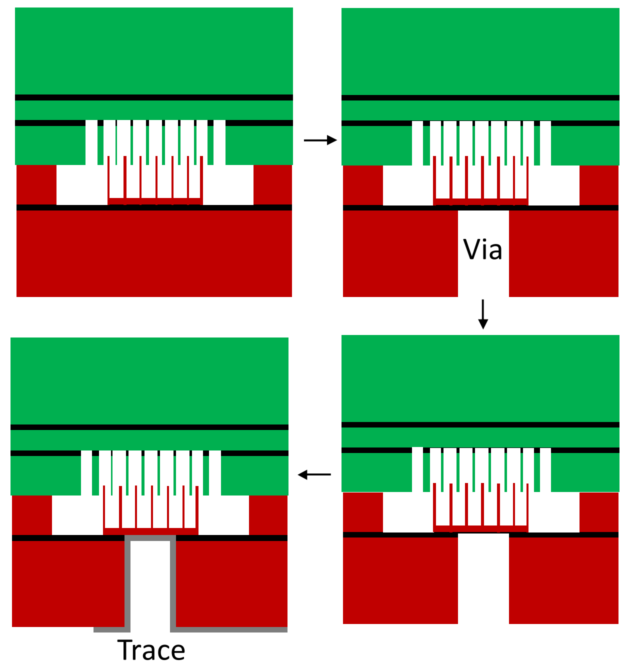


*FIGURE 4: Bonding and back electronics.*

The bonded stack is next etched from the back to form vias through the actuation plate handle wafer up to the oxide behind each comb island. The oxide is removed to provide direct electrical contact to the comb islands. Traces are then deposited down the side of the vias to provide connectivity through the wafer and out the back.

## STACK THINNING AND RELEASE

The bonded stack is thinned down to the first oxide layer on the ground plate side, at which point the oxide is used to help form a two-step etch that frees the actuator paddles as well as forming the in-plane blades. The bonding and thinning steps are shown in Fig. 5.

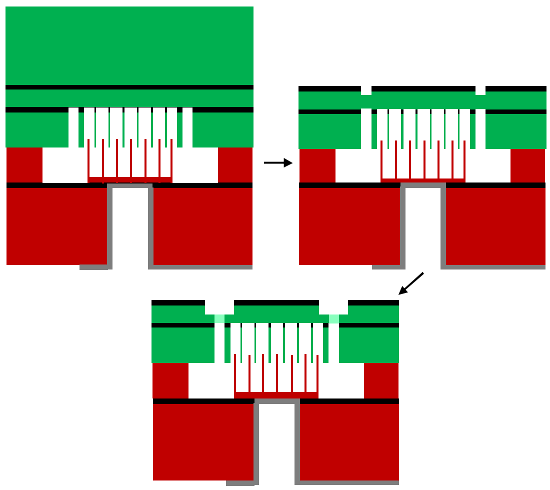

FIGURE 5: *Stack thinning and release.*

This forms the full structure, ready for attachment to the additively manufactured parts.

The resulting combs in the process are shown in Fig. 6 below and shows the desired comb array.

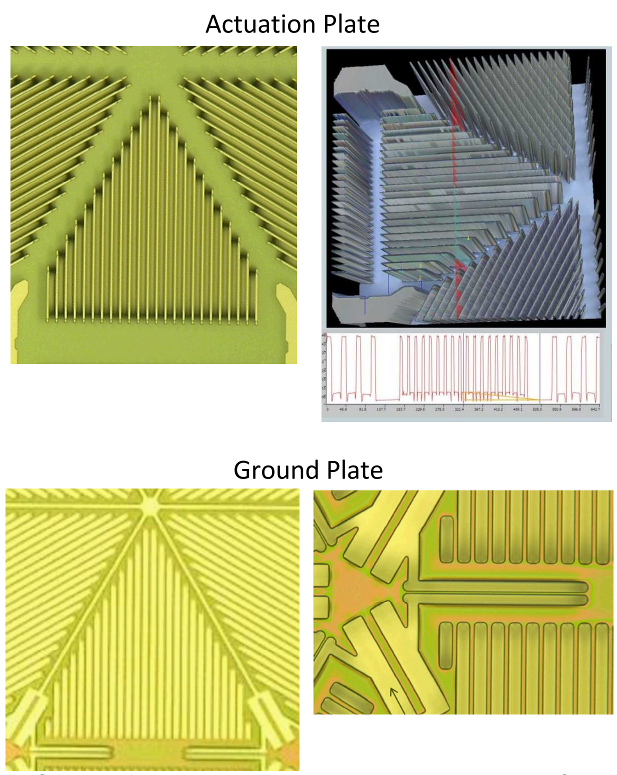


*FIGURE 6: Formed combs on both sides of the actuator.*

## ADDITIVE MANUFACTURING

The hexapod flexures, shown in Fig. 1, are generated by Projection micro-Stereolithography (PμSL) [1], carried out by exposing sequential layers of HDDA onto the back of the silicon mirrors. The performance limits of the PμSL system with both HDDA and PEGDA was studied to determine the minimum leg stiffness as shown in Fig. 7. HDDA was used due to the similar small scale performance but with reduced moisture sensitivity.

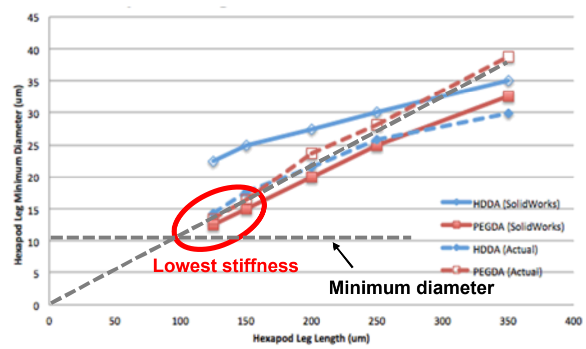


*FIGURE 7: Dimensional Limits for PμSL.*

## MIRRORS

The mirrors are fabricated in a batch process from an SOI wafer, where the device layer is cut into hexagonal patterns, gold coated, then released to form free mirrors that can be placed into the array.

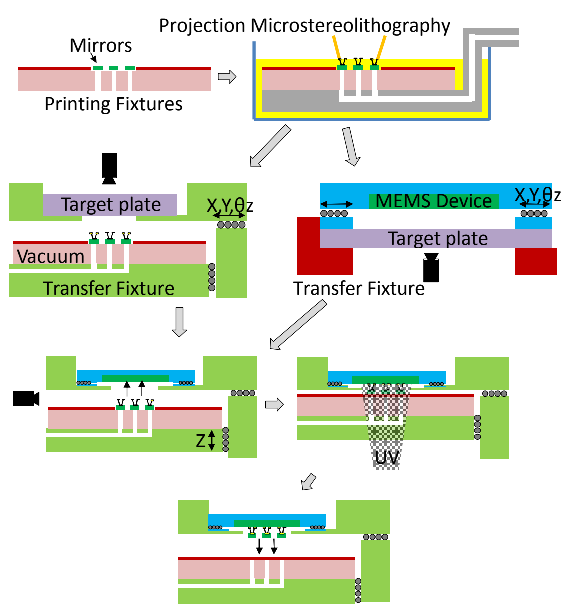


*FIGURE 8: Formed combs on both sides of the actuator.*

## HANDLING PROCESS

The mirrors are handled using two distinct fixtures. The first ‘printing’ fixture holds the seven mirrors in the correct pattern for the AM printing process. This fixture ensures the hexapod legs are printed down in a uniform pattern, and provides a means to handle the array as a single element for transfer to the final MEMS structure. The printing fixture is passed into a 'transfer' fixture, as shown in Fig. 8.

The transfer fixture is used to align the MEMS device to the hexapod+mirror array. This is done via a five step process. The first step is aligning the hexapod array to a fiducial target plate. This is done via a monocular microscope looking directly down through the glass target plate, shown in Fig. 9.

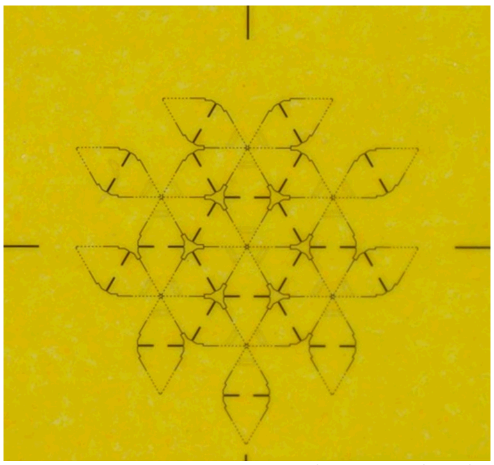

*FIGURE 9: Fiducial marks for transfer fixture alignment.*

The glass fiducial plate serves as a target to align the printing fixture to the overall frame of the transfer fixture. This process is repeated with the MEMS device aligned to an identical glass fiducial plate. The result is both the hexapod legs and the MEMS structure are aligned to the transfer fixture coordinate frame. At this point, the fiducial plates are removed, the MEMS and AM structures are touched together and the UV epoxy on the hexapod legs is cured. The mirrors are released via a positive pressure through the printing plate.

**PRINTING FIXTURE**

This fixture must simultaneously meet several requirements. It must be able to controllably and rigidly hold and release the mirrors. The fixture must provide a frame to help the mirror placement approximate that of a hexagonal array. The fixture must protect the coated side of the mirrors from the AM bath. The fixture must not alter the AM process chemistry. The surface of the fixture must have a large wetting angle with the polymer bath in the AM process, or else the thin layers of HDDA would not be able to form over the mirrors. The fixture must be resistant to the AM bath cleaning alcohols. These requirements led to the design of a multi-material printing fixture as shown in Fig. 10 and 11.

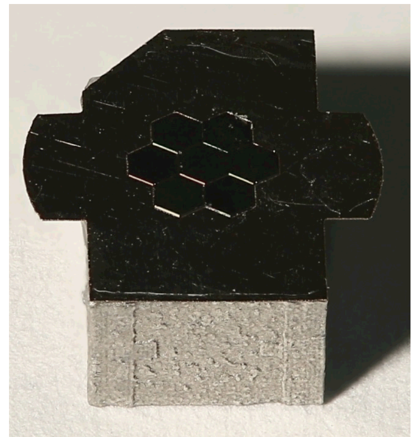

*FIGURE 10: Printing fixture with all seven mirrors inserted.*

The printing fixture is composed of an outer metal frame, with a silastic polymer cast within. The top surface of the fixture is covered with a steel plate that has a laser cut frame pattern to hold the mirrors in an array pattern.

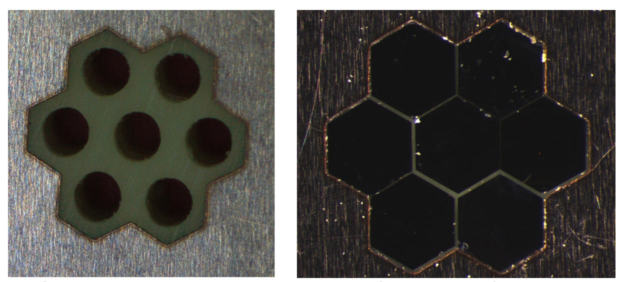

*FIGURE 11: Top down view of printing fixture with vacuum holes and polymer visible on the left, then with the mirrors placed on the right.*

This design meets all the required criteria. It has vacuum holes behind each mirror so that positive or negative pressure can be applied to the mirrors to hold or release them on command. The steel frame and top plate provide a reference frame that can hold the mirrors in an array pattern. The mirrors are placed face down against the internal polymer, and the vacuum suction holds them tightly against the polymer. This provides a robust seal against the AM bath fluids contaminating the front side. The polymer surface was found to have a low wetting angle, but the use of the steel plate on the surface mitigates that issue. Finally, the materials of the fixture are resistant to alcohols.

The printing fixture is placed on a submersible arm with a vacuum passage in it, which provides suction to hold the mirrors in place while they are in the PμSL bath. The hexapod structures are sequentially printed onto the back of the mirrors in a controlled array, resulting in the structure as seen in Fig. 12.

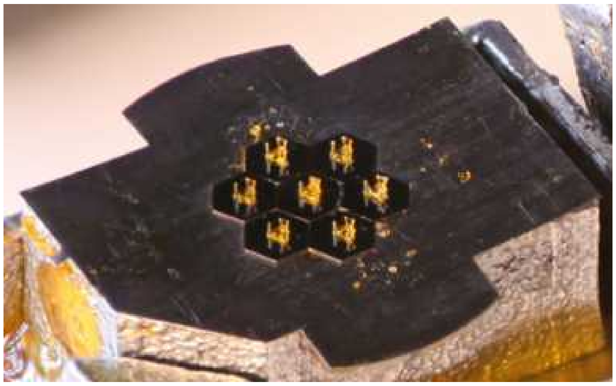

*FIGURE 12: Seven element array of printed hexapods on the seven silicon mirrors.*

The printing fixture is then passed to the transfer fixture for alignment to the MEMS device.

**TRANSFER FIXTURE**

The transfer fixture is composed of a Z-axis bearing mounted on an X-Y stage. This all lies within an optical $\theta_z$ mount which provides the full degrees of freedom needed for the alignment of the parallel structures to one another. The transfer fixture has a vacuum port to maintain the vacuum applied to the mirrors, until positive pressure is required to release the mirrors.

The fixture is shown in Fig. 13 with the printing fixture installed in the center post. This post is able to slide vertically to drive the hexapod legs up against the MEMS device. Before the final transfer is done, the hexapod legs are brought up against the glass fiducial plate, placed in a kinematic frame on the top of the structure. The X-Y stage and the $\theta_z$ stage are used to align the hexapod legs to the fiducial to within a few μm.

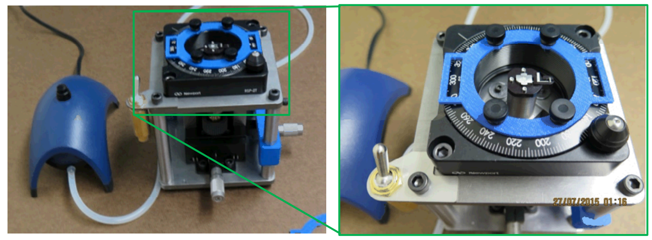

*FIGURE 13: Mirrors/hexapods transfer fixture.*

The same process is repeated with the MEMS device on a second fixture, shown in Fig. 14. This second transfer fixture has the same degrees of freedom but a different stage structure, so the MEMS chip can be firmly anchored in place.

*FIGURE 14: MEMS transfer fixture.*

This second fixture aligns the MEMS chip to the fiducial plate, at which point the MEMS chip can be transferred via kinematic mounts to the primary fixture and pressed against the hexapod legs for final transfer.

**RESULTS**

The assembly process is presently ongoing, with early tests of AM structure transfer to substrates underway. The early results are promising for the ability to do repeatable and fine motion control.

Difficulties have been observed with ensuring a vacuum seal between the mirrors and the polymer internal structure of the printing fixtures. When this fails, the vacuum system can be flooded with HDDA, resulting in the mirrors floating off the fixture. Allowing HDDA behind the mirrors also increases the release force required to pull the seven mirror array off the printing fixture during the final transfer to the MEMS device. This force must be on the few-mN scale to avoid damaging the MEMS structure paddles, so careful control of this force is required. Ongoing efforts are focused on decreasing detritus on the fixture surfaces, and using the controllable back-pressure to drive a counteracting load on the mirrors. This offers the potential to negate the stiction forces if properly tuned.

## CONCLUSIONS

A new method is described for the fabrication of a high-speed large-range micromirror array. This fabrication process draws upon both conventional microfabrication and emerging micro-AM processes to generate a 3D microscale optomechanical system.

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## REFERENCES

1. Ha, Y. M, et. al., “Mass production of 3-D microstructures using projection microstereolithography,” *Journal of Mechanical Science and Technology*, v 22, pp 514-521, 2008.